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2018

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Weld Shape Optimization for Pillow Plate Heat Exchangers

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ABSTRACT

Miniaturization of Plate Heat Exchangers (PHXs) is becoming a central research topic in order to utilize less material and less refrigerant charge to attain similar heat transfer performance, and hence contribute significantly into energy conservation and lower environmental impact. Thus, it is greatly desirable to obtain new designs to achieve this goal. Pillow Plate Heat Exchanger (PPHX) is a type of PHX with a 3D complex wavy structure, but yet an economical manufacturing process positioning itself as a potential strong competitor among other types of PHXs. PPHXs have the advantage of simple manufacturing process which gives them great design flexibility, and allows new designs to be created simpler and less costly. However, PPHXs are more commonly found in chemical and process industry. Research on PPHXs in HVAC&R is very limited. It is desired to make use of PPHXs advantages in HVAC&R applications. This can be done by creating more efficient designs. The thermal-hydraulic performance of PPHXs is primarily altered by the weld shape, size, and pattern, as well as the pillow height. The shape, and size of the weld is one of the most significant parameters affecting the thermal-hydraulic performance of PPHXs. As the weld size is smaller and more streamlined, the pressure drop is reduced significantly. However, the heat transfer area is also reduced using a more streamlined weld shape. In this study, new designs for PPHXs are investigated using different weld shapes that are represented using Non-Uniform Rational B-Splines (NURBS). Each control point in the NURBS curve is a design parameter in the optimization problem. The optimization problem has 11 design parameters. The whole CFD simulation is automated using Parallel Parameterized CFD (PPCFD). Since the CFD simulation of 3D PPHXs is computationally very expensive, the automated CFD simulations and Approximation Assisted Optimization (AAO) reduce the computational time and resources required significantly. A meta-model, using Kriging method, is calculated and verified using random samples from the design space. Multi-Objective Genetic Algorithm (MOGA) utilizes the verified meta-model to calculate optimum designs which have the optimum weld shape and size. The potential enhancement is up to 36% improvement in heat transfer coefficient and 67% reduction in pressure drop as compared to a selected PPHX baseline design with circular spot welds.

1. INTRODUCTION

The evolution of CFD in heat exchanger design added a new dimension for the design of new heat exchanger surfaces which in turn contributed to the improvement of heat exchanger performance and energy efficiency, and even became routine in some industrial applications (Shah, 2006). Shah (2006) predicted CFD will advance to the extent of conducting full 3D analysis of flows, and accurately designing complete compact heat exchangers, eliminating the need for experimental analysis. Although the need of experimental investigation is still required as a final step to validate designs, great advances took place in the last decade in computational power allowing faster CFD simulations and more accurate models to be developed. The application of CFD for the design and development of PPHXs is recently tested in literature by Piper et al. (2015) who used numerical forming simulation in order to predict the geometric characteristics of PPHXs and developed correlations for the calculation of wetted surface area, volume, and other parameters. The correlations are tested in another study by Eldeeb et al. (2016) using numerical forming simulation for PPHXs as well. While the volume agrees with the correlation within 5%, the wetted surface area correlation agrees within 20%. PPHXs are, however, still in a very early research stage.

CFD simulations with the current available computational power is essentially the most efficient, low cost, fast method to investigate novel surfaces with acceptable accuracies, especially as the complexity of the heat exchanger surface increases. The literature shows numerous examples of novel heat transfer surfaces studied using CFD (Bacellar et al., 2017; Gholami et al., 2014; Li et al., 2013; Singh et al., 2011; Wu et al., 2007; Wu & Tao, 2007). In order to make the optimization process possible with the complex 3D structure of PPHX combined with 2D NURBS weld surfaces and reduce computational time at the same time, Approximation Assisted Optimization (AAO) is employed. A predictive model is essentially created using a fixed number of expensive CFD simulations which compromise the Design of Experiments (DoE) which should provide the performance information scattered in the design space studied. Latin Hypercube Sampling (LHS) (McKay et al., 1979) is used for sampling, and Kriging (Cressie, 1993) method is used for metamodeling in the current work. The metamodel is verified using CFD simulations.

Piper et al. (2016) performed a CFD study using a turbulent single-phase water flow in PPHXs with Reynolds number ranging from 1000-8000, obtaining the PPHX surface using numerical forming simulations as well. In order to define the thermal-hydraulic performance of the PPHX, they defined an efficiency based on the total heat transfer divided by the total pumping power required. By comparing this defined efficiency, they concluded that the overall performance of PPHXs is improved using a larger pillow height, and transverse weld pattern. They also concluded that a smaller weld diameter and an oval weld shape can significantly reduce the pumping power leading to higher efficiency, although the heat transfer area is reduced as well which means lower heat transfer. Later, Piper et al. (2017) used these simulations to develop and verify heat transfer coefficient and pressure drop correlations for PPHXs. Eldeeb et al. (2018) studied the optimization of PPHXs using circular spot welds and four design parameters using AAO as well forming a verified metamodel from which a sensitivity analysis on all four design parameters is conducted. The sensitivity analysis revealed that the weld size has the most significant effect on the thermal-hydraulic performance of PPHXs. Thus, further improvement of PPHXs requires a thorough investigation and comprehensive optimization of weld shape and size specifically combined with all the other parameters as well.

In this paper, new PPHX designs with novel weld shapes are investigated using numerical methods employing NURBS, PPCFD, AAO, and a MOGA. The optimization problem has 11 design parameters, 6 of which are the related to the NURBS to represent the weld shape, 2 for weld shape parameterization, two geometric parameters, and one flow characteristic parameter. The performance is predicted through first representing the manufacturing process of PPHX, combined with NURBS weld shapes, to obtain the detailed structure of the surface using forming simulations, then studying the flow inside the surface by using suitable boundary conditions.

2. APPROACH

The outline of the current analysis and optimization procedure is shown in Figure 1 and based on the optimization method introduced by Abdelaziz et al. (2010). The PPCFD method consists of a code, written using C# in the current work, that automatically reads the Design of Experiment (DoE) input parameters and creates one Python script file, two text files, and four JavaScript files for each single design. An executable batch file is created to sequentially execute the simulations for the entire DoE. The CFD output is processed using the code as well in order to automatically process the final results for thermal-hydraulic performance. The automation outline is shown in Figure 2 comprising a Python script file which runs the entire workbench, adding the new components, calling other scripts, and CFD settings. The simulation consists of a Static Structural (SS) component in which the manufacturing process of a PPHX with NURBS weld shape is simulated and tested for mechanical failure, a Finite Element Modeler (FEM) component in which the pillow surface is converted into a Parasolid which is then transferred to the Fluid Flow (FF) component in which the Parasolid is reassembled and a computational domain is extracted, meshed, and simulated. Although automation becomes more challenging in problems with multiple components and complex geometries, however if achieved, more than 90% of engineering computational time can be saved (Abdelaziz, 2009).

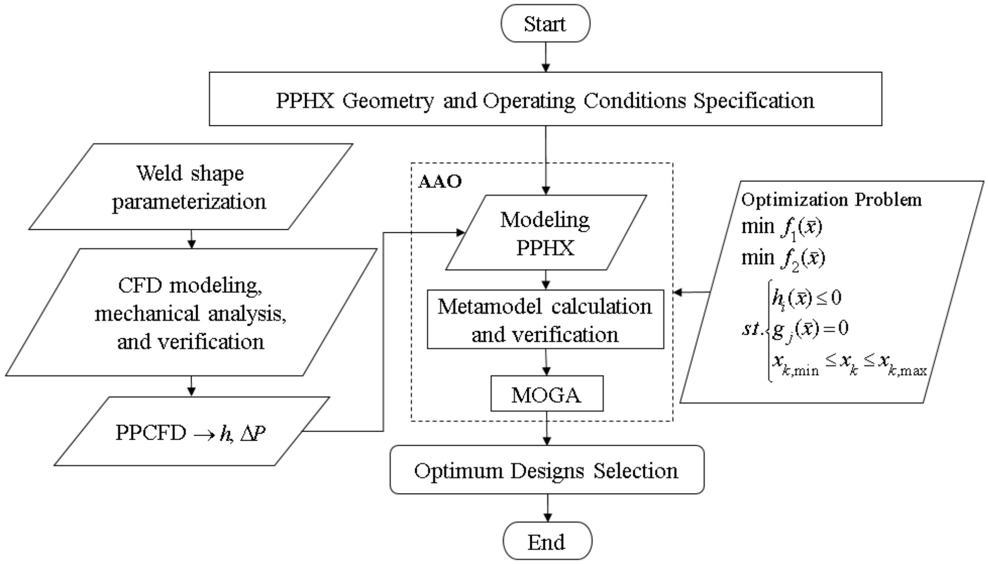

Figure 1: Optimization procedure.

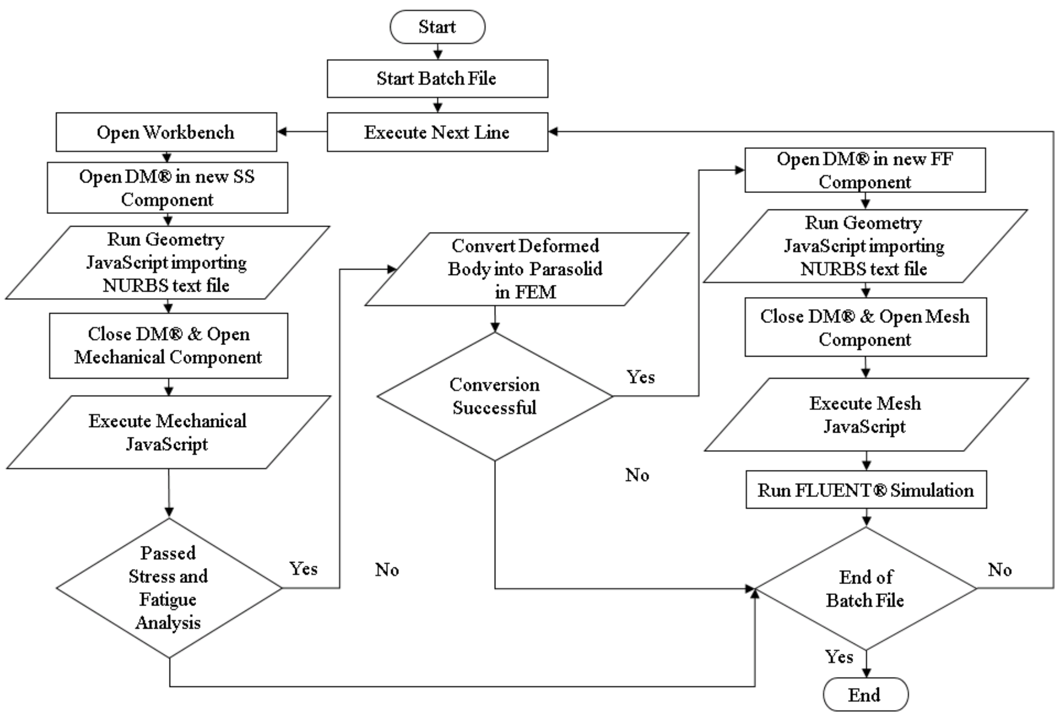

Figure 2: PPCFD Automation outline.

Once the PPCFD is executed, a metamodel is calculated and verified using random designs. In order to verify the accuracy of the metamodel, the Metamodel Acceptability Score (MAS) (Hamad, 2006) is calculated which indicates the fraction of predicted responses by the metamodel in which the absolute relative error is equal to or less than an established threshold which is 10% in the current work. Once verified, the developed metamodel accurately predicts the outcome of CFD simulation for any given design within the design space.

3. PILLOW SURFACE WITH NURBS WELD SHAPE DESIGN

The pillow surface in this study is attained by simulating the hydroforming process of two thin metal plates made of stainless steel of material 1.4541 (AISI 321) that are bonded together at the welding spots in ANSYS Static Structural (SS) component (ANSYS Inc., 2016). The Pillow Plate Heat Exchanger with NURBS weld shape (NPPHX) concept is essentially equivalent to the PPHX with the addition of the weld shape variables that describe the weld shape of the pillow. The design space consists of 11 design variables from which 6 are the x and y normalized coordinates of the control points used to describe the weld NURBS curve as shown in Figure 3. Additional two fixed control points denote the leading edge and the trailing edge of the NURBS. The result is a 4th order NURBS curve. The design space of the NPPHX is shown in Table 1.

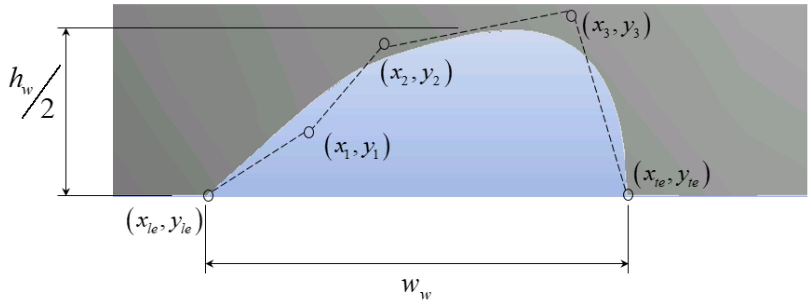

Figure 3: NPPHX weld shape parameterization.

Table 1: NPPHX design space.

Variable Type	Design Variable	Unit	Range
Scaling	h_w	mm	3.0-10.0
	w_w / h_w	–	1.0-2.0
Topology	$2s_L / s_T$	–	0.58-1.73
	h_p	mm	3.0-12.0
Shape	x_i , where $i = 1, 2, 3$	–	0.0-1.0
	y_i , where $i = 1, 2, 3$	–	0.0-1.0
Fluid	v_{in}	$m \cdot s^{-1}$	0.1 - 2.0

4. CFD

The flow studied is single phase, incompressible, turbulent, steady-state water flow with fluid CFD simulations performed using ANSYS FLUENT® (ANSYS Inc., 2016), which is based on finite volume method. The front view of the computational domain of one of the designs and its 3D view are shown in Figure 4. The computational domain consists of five segments of the basic periodic symmetrical cell of the pillow surface in order to capture both the entrance region and the steady state region. Assumptions of homogeneous inlet velocity, constant outlet atmospheric pressure (0.0 Pa gauge), and symmetrical pillow sides are applied. Additionally, no-slip boundary condition and constant wall temperature are applied as well. The Reynolds number in this study is defined using:

$$Re = \frac{u d_h}{\nu}, \; where \; d_h = \frac{4V}{A_w} \tag{1}$$

The heat transfer coefficient is calculated using the logarithmic mean temperature difference (LMTD) method using:

$$h = \frac{Q}{A_{w,i} LMTD} \quad (2)$$

The friction factor is calculated using:

$$f = \frac{d_h}{2 \rho u^2} \left(\frac{\Delta P}{L} \right) \quad (3)$$

The baseline case is selected to be one of the optimum designs for the PPHX with circular spot welds obtained by Eldeeb et al. (2018). The inlet temperature is 295 K and the wall temperature is 300 K. The pressure-velocity coupling scheme used is the SIMPLEC solver available in ANSYS FLUENT® (ANSYS Inc., 2016). All space discretization schemes are second order degree upwind. This is done to obtain good accuracy with relatively low computational cost, as the 3D CFD simulations of PPHX plates are very computationally expensive. Grid Convergence Index (GCI) method (Roache, 1998) is used for the verification of the CFD models using meshes with different mesh refinement sizes. Three grid resolutions for each case are studied. The GCI analysis results is shown in Figure 5.

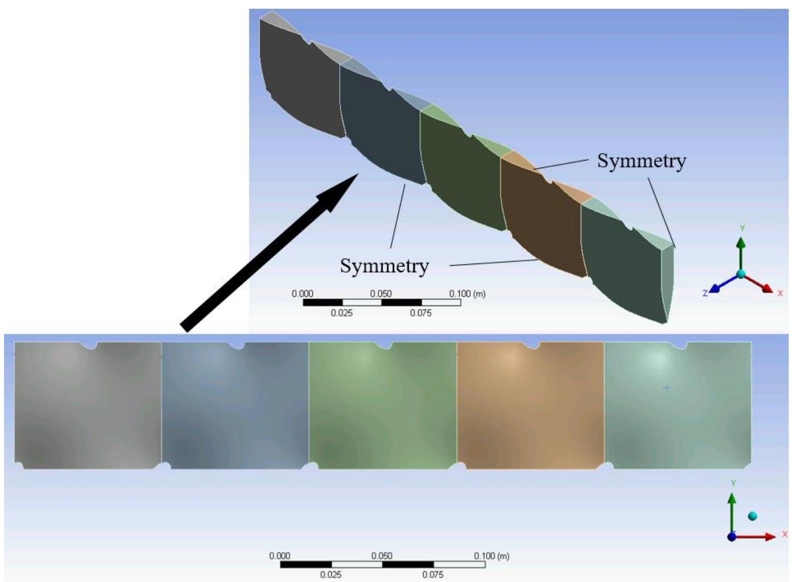

Figure 4: Front and 3D views of a NPPHX computational domain.

Table 2: NPPHX Optimization Baseline.

Baseline	$s_T / 2s_L$ (-)	h_i (mm)	d_{sp} (mm)	v_{in} (m/s)
PPHX-073	0.75	12.0	5.7	1.99

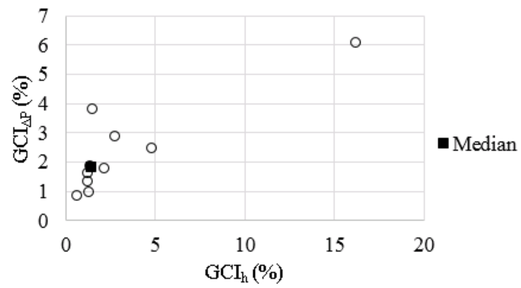

Figure 5: GCI analysis for NPPHX.

5. METAMODEL VERIFICATION

An effective 1764 samples from the DoE generated using LHS are simulated successfully and used to create the metamodel. The metamodel is verified using 354 random designs shown in Figure 6(a) for the heat transfer coefficient and in Figure 6(b) for the pressure drop per unit length. The metamodel verification metrics are shown in Table 3.

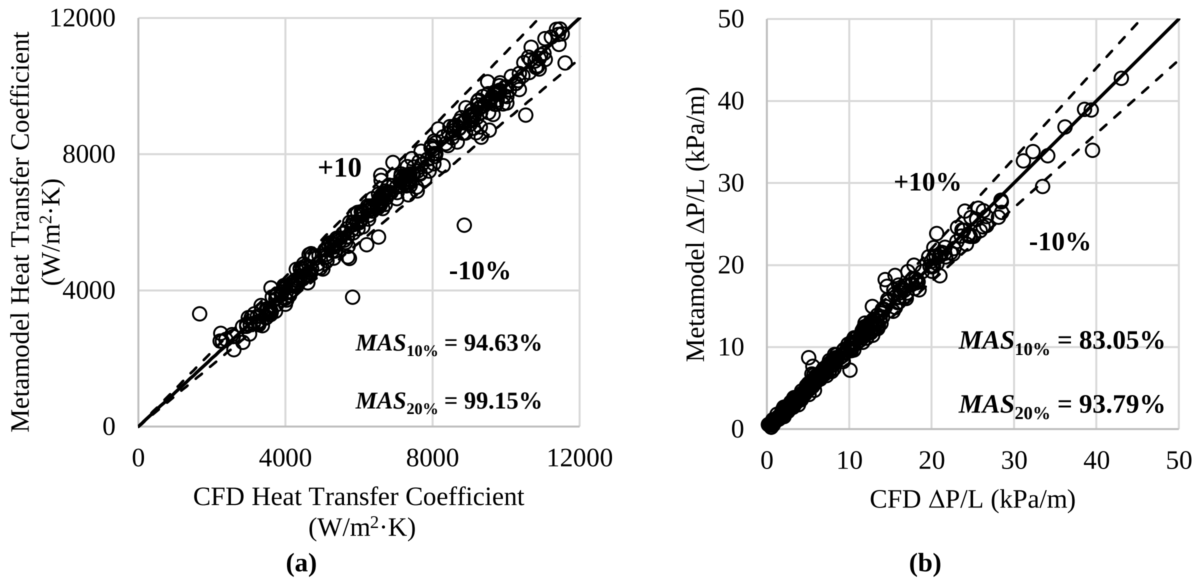

Figure 6: NPPHX metamodel verification for (a) heat transfer coefficient, and (b) pressure drop, against 354 random designs.

Table 3: NPPHX metamodel verification metrics.

Interpolated variable	Heat Transfer Coefficient	$\Delta P / L$
Number of samples	1764	
Number of random samples	354	
Kriging Correlation	Gaussian	Spline
Kriging Regression model	Polynomial 2nd order	Polynomial 2nd order
Root Mean Square Error (RMSE)	14.78	0.713
Relative RMSE (%)	1.92	2.69
MAS' threshold (%)	10	10
MAS (%)	94.63	83.05

6. RESULTS

6.1 Sensitivity Analysis

The verified metamodel is used to conduct a sensitivity analysis on some of the design variables to investigate and verify their impact on the thermal-hydraulic performance. For each parametric study, a single variable is changed while all other variables are fixed. The reference values used for each design variable in all studies are 1.73 pitch ratio, 12.0 mm pillow height, 5.0 mm weld height, 2.0 for the weld width-height ratio (WHR), 2.0 m·s^{-1} inlet velocity, and the same weld shape shown in **Figure 7**. Figure 8 shows the results of the parametric analysis run on the weld height, and WHR. All parameters are normalized.

Figure 7: Weld shape used in sensitivity analysis.

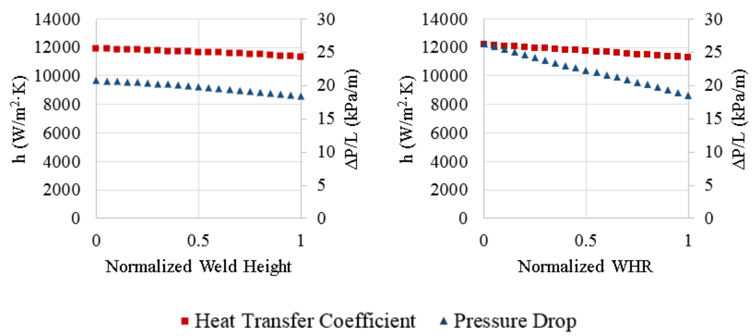

Figure 8: NPPHX sensitivity analysis for some normalized design parameters.

Parametric analysis on weld pitch ratio, inlet velocity, and pillow height are also conducted and the results are consistent with the parametric analysis done by Eldeeb et al. (2018) but not presented here due to space limitations. Eight parameters describe the weld shape and size in this problem, six of which are the control points coordinates and they are fixed for this parametric analysis, while the other two, the WHR and the weld height, are varied independently. Figure 9 shows the velocity profile of different NPPHX designs with different weld shapes. The fluid enters from the far right end in all figures.

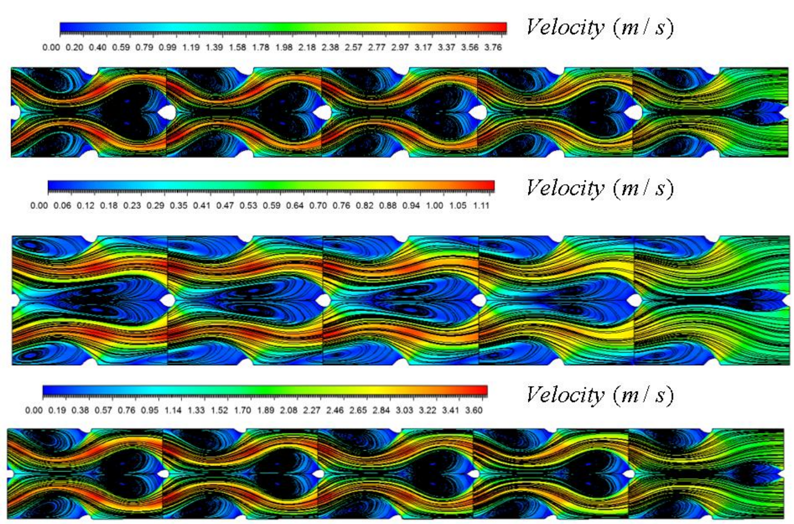

Figure 9: Velocity profile of NPPHX designs with different weld shapes

Generally smaller more streamlined welds yield lower pressure drop values. The thermal-hydraulic performance is almost affected in a similar pattern by changing any of these two parameters, with the WHR reducing the pressure drop more sharply since the pressure drop is high for smaller values of WHR. As the size of the weld increases, the heat transfer area is reduced, and thus the heat transfer coefficient decreases as well. However, if the increase in size means a more streamlined weld as well, with higher WHR values, the pressure drop is significantly reduced as a result as well since the wake region behind the weld is reduced. Figure 10 shows the velocity profile for two different NPPHX designs. The wake region behind the NPPHX design with the lower WHR value is obviously larger than the design with the more streamlined weld shape with a higher WHR value, thus yielding a lower pressure drop.

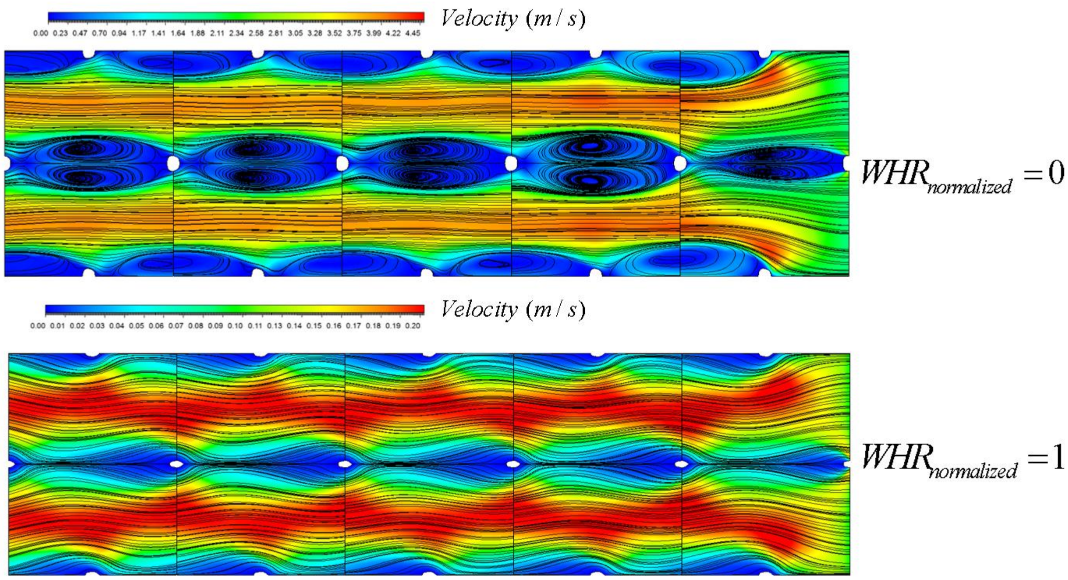

Figure 10: Velocity profile for different weld width-height ratio values.

6.2 Optimum Designs

A multi-objective optimization is conducted using a MOGA and the verified metamodels to optimize the thermal-hydraulic performance of NPPHX. The optimum NPPHX designs are presented in Figure 11 compared to the baseline. The baseline is given in Table 2. As expected, the more streamlined weld shape led to a significant reduction in pressure drop. The heat transfer coefficient on the other hand is either improved, or slightly affected by the change.

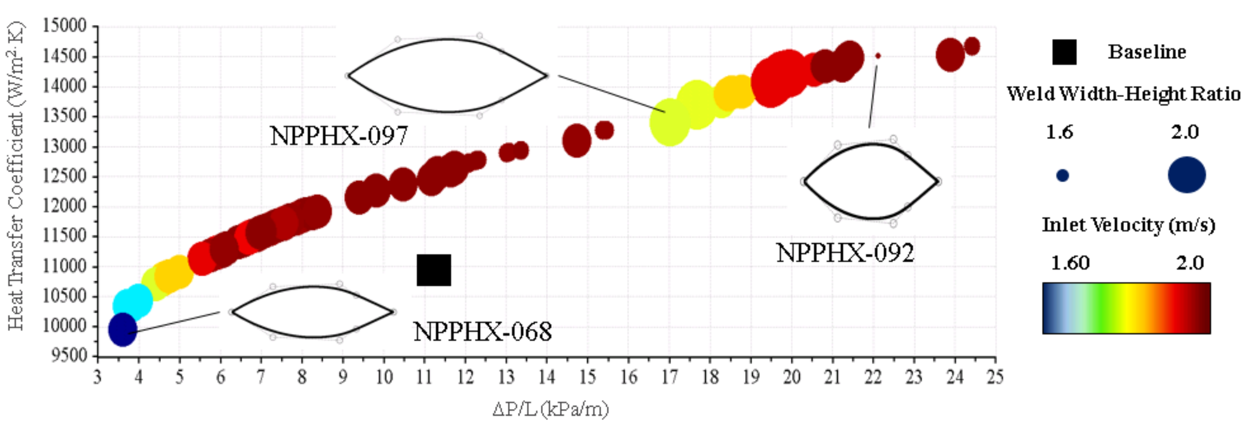

Figure 11: Optimum NPPHX designs at different weld width height ratios and inlet velocity.

The WHR for the optimum designs ranges from 1.6 mm to 2.0 mm which means more streamlined weld shapes. The effect of increasing the inlet velocity is directly proportional to both the heat transfer coefficient and the pressure drop. Some of the best designs right at the middle of the Pareto have both moderate WHR and moderate inlet velocity leading to a tradeoff between higher heat transfer coefficient and moderate pressure drop values. The optimum NPPHX designs have pitch ratios ranging from 0.58-1.36. Higher pitch ratios describe longitudinal weld patterns which have higher heat transfer coefficient and higher pressure drop values, while transverse weld pattern have lower heat transfer coefficient and lower pressure drop. The pillow height and the inlet velocity for the optimum NPPHX designs are both in their respective high ranges of 11.45 mm to 12 mm, and 1.6 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$, respectively, which is quite expected due to their favorable effect on thermal-hydraulic performance.

The optimization results show an improvement in the heat transfer coefficient ranging from at least 5% at moderate pressure drop values and up to 36% at high pressure drop values (of about 24.4 kPa/m) with respect to the baseline with circular spot welds. The optimization results also show a significant reduction in pressure drop per unit length ranging from at least 10% at moderate heat transfer coefficient values and up to 67% at lower heat transfer coefficient values relative to the baseline.

7. CONCLUSIONS

A optimization study that includes weld shape analysis using novel weld shapes generated using NURBS is presented. PPCFD and AAO are utilized which includes the automation of CFD simulations in order to simulate hundreds PPHX novel designs and use the responses to generate a verified metamodel. The metamodel is then used to run a sensitivity study and a MOGA to optimize the performance of PPHXs with NURBS weld shape. The optimization results show a significant reduction in pressure drop per unit length of up to 67% reduction relative to the baseline which is selected from optimum PPHX designs with circular weld shapes. The heat transfer coefficient is also improved by up to 36% relative to the selected baseline. The sensitivity analysis clearly shows that a more streamlined smaller weld results in the optimum designs with better improvement in thermal-hydraulic performance of PPHXs.

NOMENCLATURE

A_w	wetted area	(m^2)	s_L	Longitudinal spot weld pitch	(m)
d_h	hydraulic diameter	(m)	s_T	transverse spot weld pitch	(m)
GCI	Grid Convergence Index	(-)	v_{in}	inlet velocity	($m \cdot s^{-1}$)
h_w	weld height (m)	(m)	WHR	weld width-height ratio	(-)
h_p	pillow height	(m)	w_w	weld width	(m)

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ACKNOWLEDGEMENT

This work was supported by the Modeling and Optimization Consortium (MOC) of the Center for Environmental Energy Engineering (CEEE) at the University of Maryland College Park.